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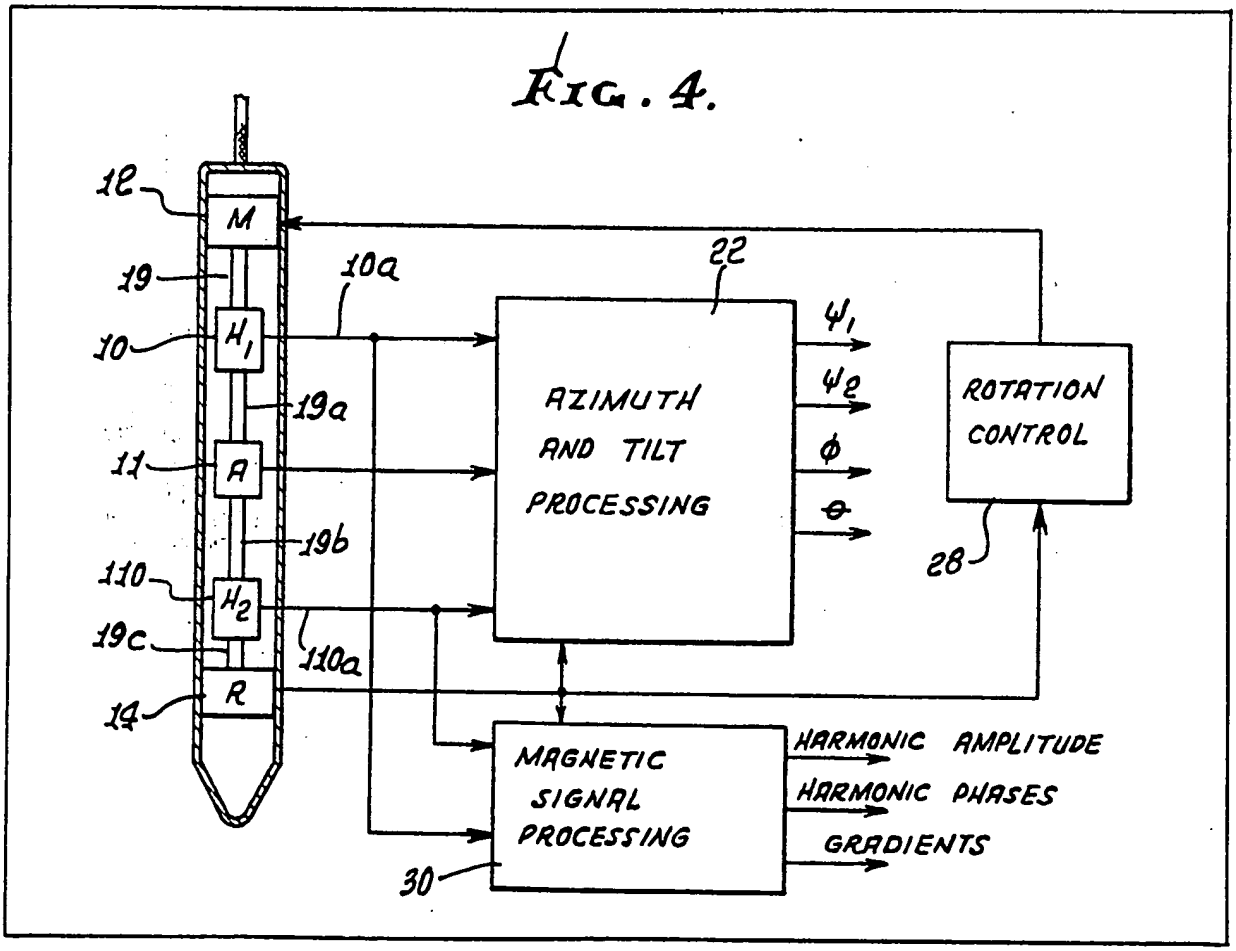
(54) Well mapping apparatus

(57) Well mapping apparatus comprises
a) a magnetic field sensing device (10) whose output is proportional to a local magnetic field vector; and possibly a further such device (110), the two outputs being averaged,
b) an acceleration sensing device (11) whose output is proportional to a local gravity vector,
c) the devices being supported for rotation by a motor 12 about a common axis, in a borehole,
d) the outputs being usable in the determination of azimuth and inclination of the borehole. The devices can be fitted relative to the axis of rotation of the motor 12.



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The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.

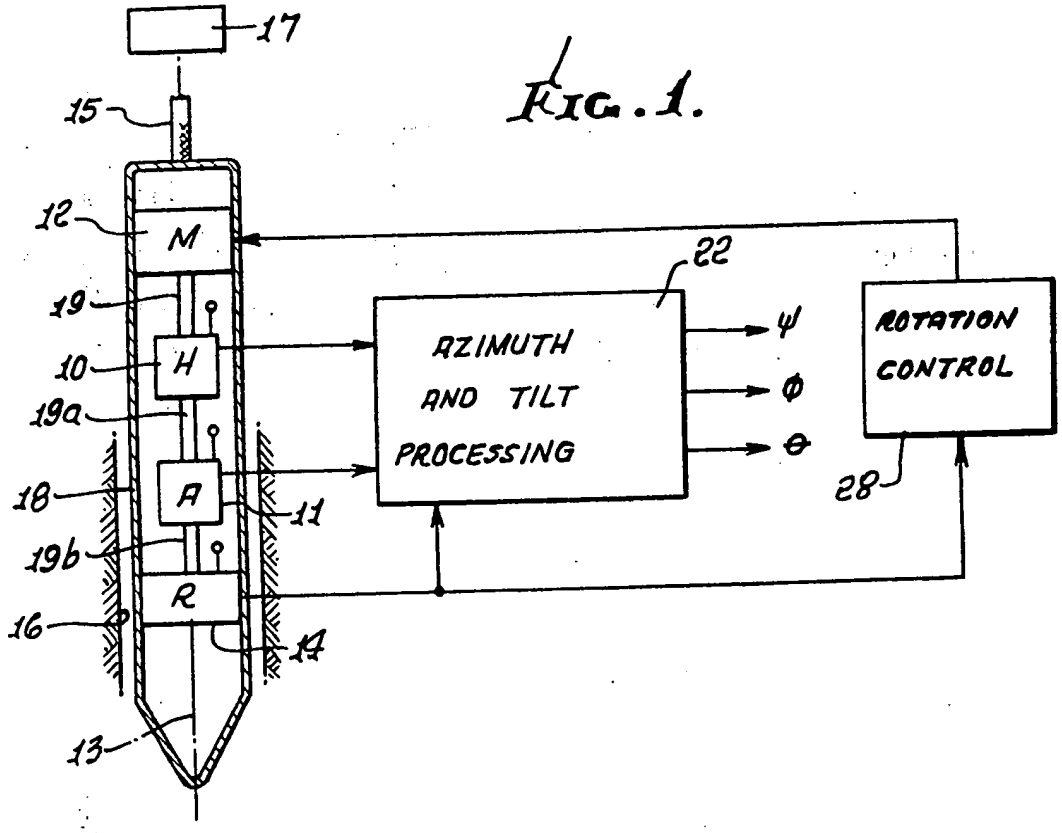


FIG. 1.

FIG. 1a.

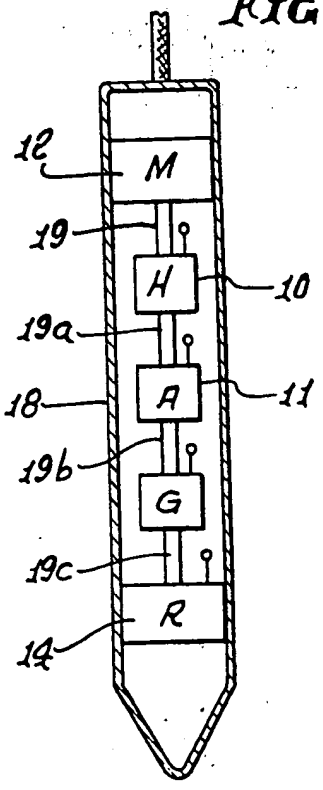


FIG. 2.

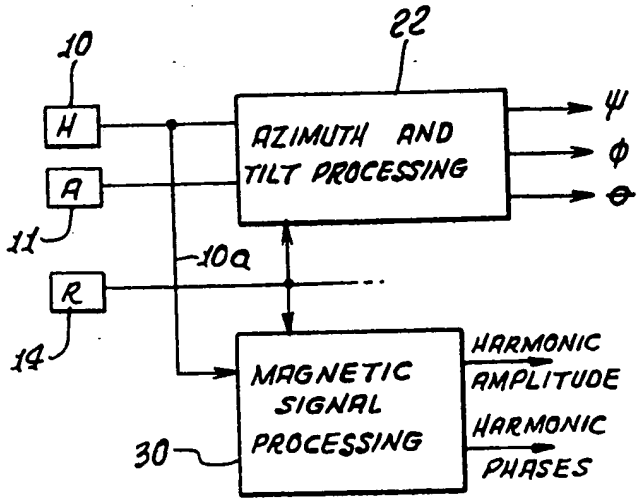


FIG. 3.

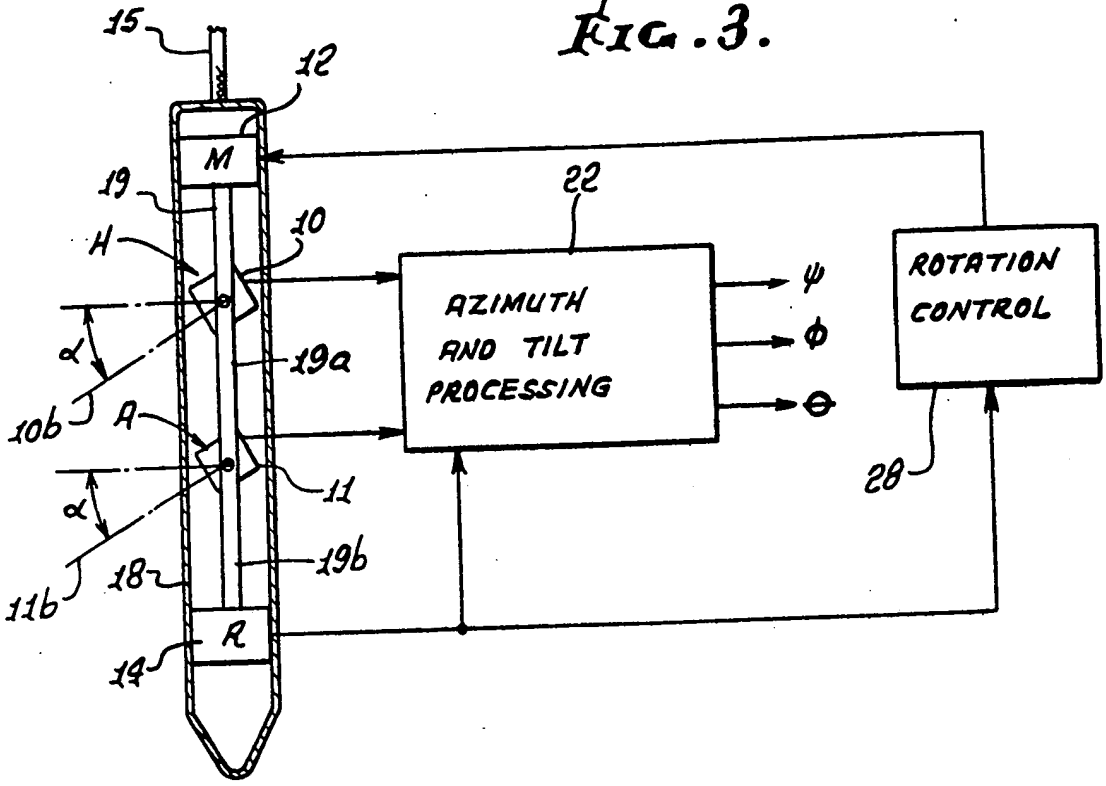

15
12
M
19
10
H
22
AZIMUTH AND TILT PROCESSING
ψ
φ
θ
ROTATION CONTROL
α
19a
10b
A
11
α
11b
18
19b
28
R
14

FIG. 4.

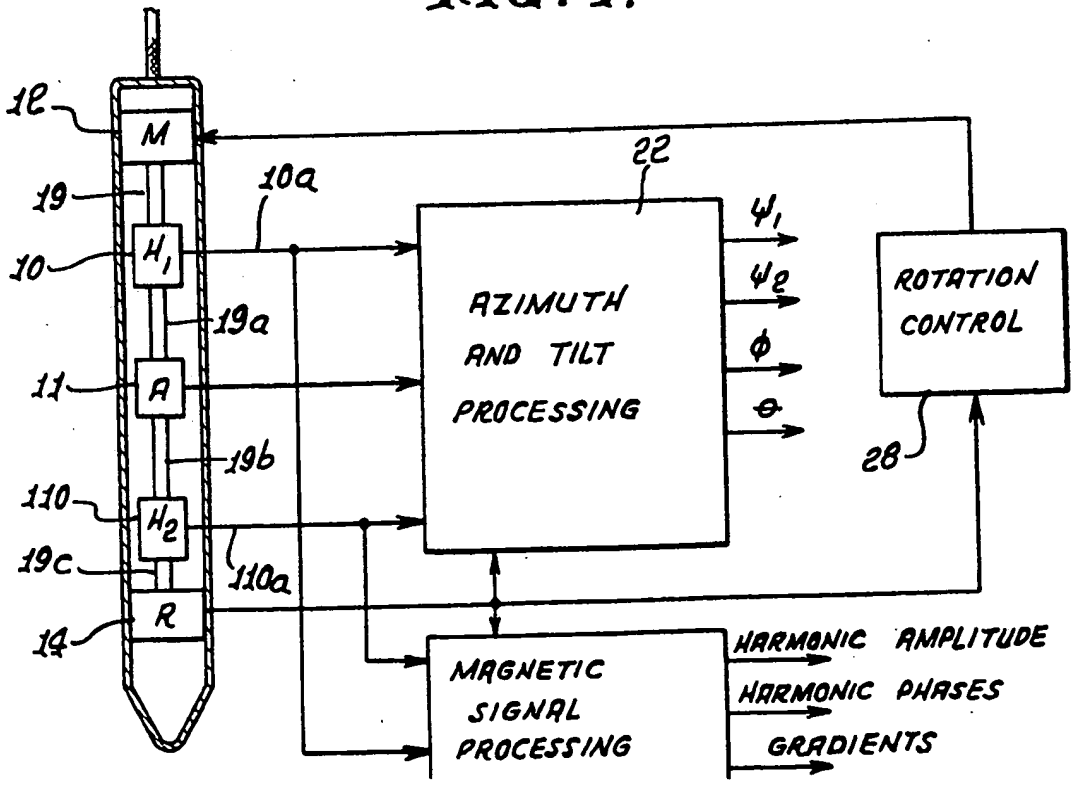

12
M
22
10a
19
10
H1
ψ1
ψ2
AZIMUTH AND TILT PROCESSING
ROTATION CONTROL
φ
θ
19a
11
A
19b
28
110
H2
19c
110a
R
14
MAGNETIC SIGNAL PROCESSING
HARMONIC AMPLITUDE
HARMONIC PHASES
GRADIENTS

FIG. 5.

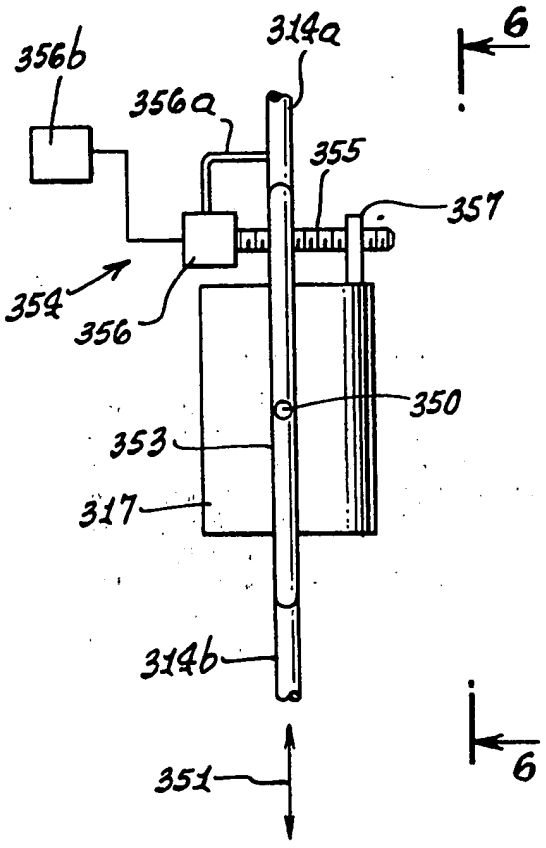
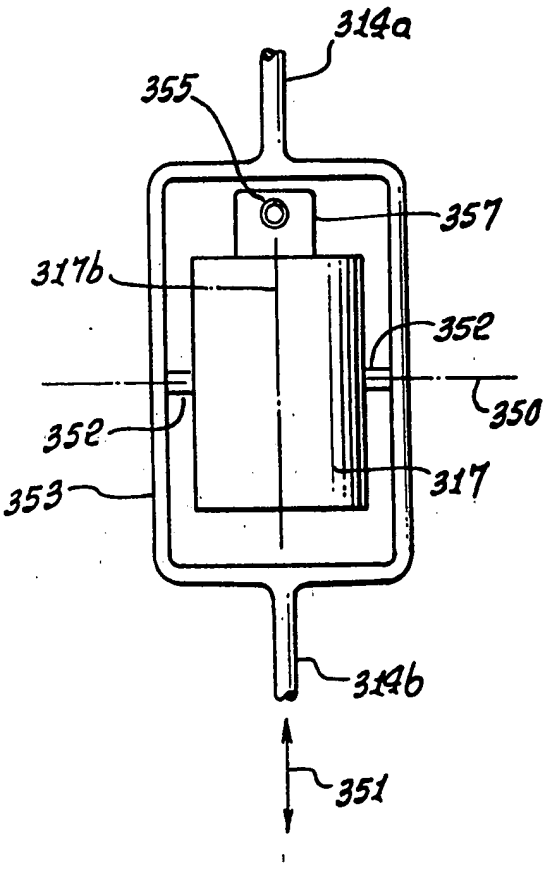

314a
6
356b
356a
355
357
354
356
350
353
317
314b
351
6

FIG. 6.


314a
355
357
317b
352
350
352
353
317
314b
351

SPECIFICATION

Well mapping apparatus

This invention relates generally to surveying of boreholes, and more particularly concerns apparatus and methods to determine azimuth and tilt, employing magnetic means to determine azimuth. This invention also relates to detecting errors in magnetic azimuth, local magnetic anomalies, or nearby magnetic objects.

It is known to use an angular rate sensing gyroscope and an accelerometer in a rotating gimbal to detect both the earth's rotation rate vector and the gravity vector. Each instrument provides an output that is proportional to the vector dot product between the sensor input axis and its associated reference vector, plus certain error terms. Analysis shows that borehole tilt and azimuth may be computed from these sensor outputs, and that the gimbal rotation makes it possible to both measure all required data with only one sensing axis of each kind and to eliminate major bias type error sources from the sensors.

Also, it is known to use magnetometers in borehole surveys; however, no way was known to employ a single magnetometer to determine azimuth, in the unusually advantageous manner as described herein.

It is a major object of the invention to provide method and apparatus wherein a magnetic field sensing device may be employed in an advantageous manner and along with an accelerometer, to provide outputs usable in determination of borehole azimuth and tilt at instrument locations in the hole. Also provided are secondary usable outputs indicating errors in magnetic azimuth, local magnetic anomalies, or nearby magnetic objects.

The present invention is well mapping apparatus comprising (a) a magnetic field sensing device whose output is proportional to a local magnetic field vector, (b) an acceleration sensing device whose output is proportional to a local gravity vector, and (c) means supporting said devices for rotation about a common axis, in a borehole, (d) said outputs being usable in the determination of azimuth and inclination of the borehole.

As will appear, the above devices may be simultaneously rotated about the common axis, and circuitry is provided to receive the device outputs to derive azimuth and inclination of the borehole; apparatus may be provided to receive the output of the magnetic field sensing device (as for example a magnetometer) to provide an harmonic analysis of the output, whereby errors in azimuth determination, local magnetic anomalies, or nearby magnetic objects may be detected; the angularity of the field sensing device and/or that of the accelerometer may be canted to improve the output signal, as for example its amplitude; a second magnetic field sensor may be provided and connected to assist in determining field gradient; and an inertial angular rate sensor may be coupled with the instrumentation, for purposes as will appear.

Embodiments of the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:—

Fig. 1 is an elevation taken in section to show one form of instrumentation employing the invention;

Fig. 1*a* is a view like Fig. 1;

Fig. 2 is a circuit block diagram;

Fig. 3 is a view like Fig. 1, but showing modified instrumentation;

Fig. 4 is another view like Fig. 1, but showing further modified instrumentation, and also a circuit block diagram;

Fig. 5 is a fragmentary elevation showing variable cant mechanism as usable in the Fig. 3 instrumentation; and

Fig. 6 is a side view taken on lines 6—6 of Fig. 5.

Consider first an arrangement as shown in Fig. 1. The arrangement comprises first a magnetic field sensing device 10 (or magnetometer) whose output is proportional to a local magnetic field vector; second, an acceleration sensing device 11 whose output is proportional to a local gravity vector; and, third, a means 12 to rotate these devices about an axis 13 which will generally be along a borehole axis. The means to provide rotation may, for example, be a geared timing type motor to provide continuous rotation, or a servoed type motor working with an angle sensor about the rotation axis to provide either continuous rotation or discrete positioning. These devices, along with a resolver 14, are located in a container or carrier 18 that is suspended by cable 15 in a borehole 16, and travelled therein by surface means 17. Motor output shaft 19 has extensions 19*a* and 19*b* to rotate devices 10 and 11, and provide input to the resolver which is also tied to the container. See also Figs. 1 and 6 in U.S. Patent Application 293,159 filed August 17, 1981.

For this configuration, both the magnetic field and acceleration sensing devices 10 and 11 (i.e. H and A) have single axes of sensitivity, nominally positioned parallel to each other and normal to the rotation axis 13. As the combination of sensing devices is rotated about its rotation axis 13 in a borehole, both the magnetic field sensing and acceleration sensing devices 10 and 11 will produce variable output indications proportional to the vector dot product of a unit vector along the respective input axis and the local magnetic field vector and gravity vector respectively. For continuous rotation operation at a fixed location in the borehole and a uniform earth's magnetic field, these signals will be sinusoidal in nature. For discrete step rotation, the sensor output will be just the equivalent of sampling points on the above mentioned sinusoidal signals. Thus, from a knowledge of sample point amplitudes and position along the sinusoid the character of an equivalent sinusoid in amplitude and phase may be determined.

The output sinusoidal signals from the acceleration sensing and magnetic field sensing

devices may be combined and processed as in circuitry indicated at 22, and which may be located in carrier 18 or at the surface to provide the azimuth direction of the borehole axis with respect to the vertical plane containing the direction of the local earth's magnetic field. The output signal from the acceleration sensing device 11 alone may be used to determine the tilt or drift of the borehole axis with respect to the local gravity field vector. Such determinations of directional azimuth and tilt or drift from vertical are free of any constant or bias type errors of the sensing devices.

The combination of elements as described above is considered as superior to such other rotatable magnetometer systems as disclosed in U.S. Patent 4,174,577, since there is in the present case no requirement for a flexible drive shaft, or for the two axis pendulous gimbal system required to maintain the magnetometer so that it only senses the horizontal component of the earth's magnetic field. Also, the use of an acceleration sensing device of any desired accuracy can provide much improved direction and tilt measurement than those obtainable from a self-pendulous approach.

It should be noted that the signal processing used to derive azimuth direction and tilt or drift from the sinusoidal signal outputs from the magnetic field and acceleration sensing devices 10 and 11 is essentially identical to that disclosed in U.S. Patent 3,753,296 to Van Steenwyk in which a single axis gyroscope is employed rather than the magnetic sensing device of the present invention. Note in this regard that the present configuration provides azimuthal direction with respect to the plane containing the local earth's magnetic field vector, whereas the apparatus in the Van Steenwyk patent provides azimuthal direction with respect to true north as defined by the earth's rotation rate vector. Circuitry 28 connected in feedback relation between resolver 14 and motor 12 controls the latter in response to resolver output.

The addition of a magnetic signal processing means 30 which may be located in carrier 18 or at the surface is shown in Fig. 2. It receives the output of device 10 *via* lead 10*a* and processes same to provide an harmonic analysis of the magnetic sensor output signal. Thus means 30 is an harmonic analyser, having amplitude and phase output. If the local magnetic field is solely that of the earth's field, the output waveform is a sinusoid at the frequency of rotation of shaft 19, and the sinusoid amplitude should match that of the sensed component of the assumed known earth's magnetic field. Any observed deviation of the magnetic signal from the above described ideal is an indication of some anomalous magnetic field condition that may influence the accuracy of the magnetically determinable azimuth direction. Analysis of the frequency and amplitude characteristics of the deviations from the ideal earth's magnetic field may be used to quantify the probable errors of such magnetic azimuth determination. Such magnetic signal processing can be by either a commercial analyser or special purpose circuits.

A further aspect of the invention concerns canting the input axis or axes 10*b* and 11*b* of either or both of the sensing devices 10 and 11 by a selected angle, α, as shown in Fig. 3. That angle may be fixed for a given configuration or may be variable within a given configuration. The cant angle may be typically on the order of 10 to 30 degrees, but variable angle arrangements can provide capability for variation as great as 0 to 90 degrees. The introduction of a cant angle adds the capability to measure three orthogonal components of either the gravity field or magnetic field with the previously described single axis sensors. The components normal to the rotation axis continue to be determined error free. When the apparatus is periodically operated with the cant angle adjusted to zero, the true sensor bias error may be determined. If, subsequently, the cant angle is adjusted to an angle such as 10 or 20 or 30 degrees, measurements free of fixed bias type errors may be made for all three components of the sensed quantity.

Figs. 5 and 6 illustrate technique for adjusting the angularity of the axis of sensitivity of the accelerometer relative to the lengthwise direction of instrument travel in the borehole. As shown, the accelerometer 317 (corresponding to accelerometer 11) has an axis of sensitivity (input axis) shown at 317*b*, which is rotatable about an axis 350 which is substantially normal to the direction of travel 351 in the borehole. Shaft extensions 314*a* and 314*b* correspond to extensions 19*a* and 19*b* in Fig. 1. The accelerometer 317 is carried by pivots 352 in a frame 353 to which shaft extensions 314*a* and 314*b* are connected, as shown. Control means 354 is also carried by the frame to adjust the cant of axis 317*b*, as for example at locations of operation as described above, to improve the determination of azimuthal direction of tilt of the borehole, at "calibration" locations, and/or at other instrument locations in the hole. The control means 354 may, for example, comprise a jack screw 355 driven by a reversible motor 356 suspended at 356*a* by the frame. The jack screw extends laterally and interfits a nut 357 attached to the accelerometer case, as for example at its top, offset from axis 350. A servo system 356*b* for the drive may be employed, so that a chosen angularity of axis 317*b* relative to direction 351 may be achieved. Support or suspension 356*a* may be resiliently yieldable to allow the accelerometer to be adjustably tilted, without jamming of the drive or screw.

When desired, a system similar to that of Figs. 5 and 6 may be used to cant the angle of the sensitive input axis of the magnetic field sensing device 10.

The addition of a second magnetic field sensing device 110 as shown in Fig. 4 provides additional capabilities. First, if operated just as the first magnetic field sensor 10, it provides a second

determination of magnetic azimuth direction which may be used to detect error by direct averaging of first azimuth determination ψ_1 with the second determination ψ_2. Such averaging may be conducted by addition and dividing circuits in block 22

$$\frac{\psi_1 + \psi_2}{2}.$$

Alternatively, the device ouptuts may be averaged, and the result processed to derive an average azimuth. It also provides redundancy such that measurements are still obtainable from device 110 if the first magnetic field sensing device 10 should fail. Most importantly, the second magnetic field sensing device 110 may be used to improve the detection of anomalous magnetic fields in the region of the sensors. Assuming that the only magnetic field in the region of the sensors is that of the earth's magnetic field, both the first and second magnetic field sensors 10 and 110 produce identical outputs $H(t)_1$ and $H(t)_2$. Since the spacing along the borehole axis is typically on the order of two to five feet, the difference of the two magnetic sensor outputs $H(t)_1$—$H(t)_2$ (on leads 10*a* and 110*a*) is a measure of the gradient of the local field. With the previously discussed cant angle α for the magnetic sensing device 10 set to zero, gradients S_1 of the cross borehole components with respect to the along borehole direction are measured. The gradient S_2 of the along borehole component with respect to the along borehole direction is also measured with the cant angle set to α (where α may be up to 90°). As with the single magnetic sensing device arrangement, the individual output signals of both cantable sensors may be analysed by the magnetic signal processing circuit 30 to provide additional detail characterization of any anomalous magnetic fields.

The arrangements described above could also make use of acceleration sensing and magnetic field sensing devices having more than one axis of sensitivity. Both two and three axes of sensitivity may be used to provide increased redundancy for improved reliability or accuracy whenever the increased complexity of such sensors is acceptable.

Although the discussions above concerning the use of harmonic errors of the magnetic sensor outputs or of the availability of gradients of the local magnetic field related to the ability to detect errors in the magnetically derived azimuth output, it is also possible to use these same data as means for determining the proximity of the sensor unit to known or expected anomalous magnetic fields resulting from pieces or parts of magnetic materials or from their effects in distorting the uniform earth's field. Thus such outputs could be used for the detection and direction indication of such elements.

Another useful combination employs a means indicated at G in Fig. 1*a* (to be rotated by shaft 19) for sensing angular rate with respect to inertial space in any or all of the arrangements shown in Figs. 1 to 4. Such means can be provided to measure angular rate in one, two, or three axes of an orthogonal coordinate set. See U.S. Patent Application 293,159, referred to above. The inclusion of such an inertial rate sensing device permits the additional measurement of the earth rate rotation vector from which an azimuthal direction with respect to a true north direction can be found. This addition provides the capability to survey magnetic variation (the angle between true north and magnetic north), to initialize magnetic direction sensing instruments in relation to true north, or to operate in borehole survey operations or borehole magnetic anomaly detection operations in a precise manner with only one multi-purpose sensing array.

Magnetic field sensing devices (magnetometers) may be of any type, such as flux gate type, Hall effect type, or nuclear magnetic resonance type. The magnetic signal processing function may be supplied to a commercial harmonic analyzer of any type that provides harmonic amplitudes and phases of the input sensor data, or it may comprise special purpose cirucits designed as a part of the sensor system.

Examples of usable magnetometers are as follows:

Model	Manufacturer
Magnetometer	Develco, Inc.

Examples of usable harmonic analysers 30 are as follows:

Model	Manufacturer
3582A	Hewlett-Packard
5920A	Hewlett-Packard

In the drawings ψ refers to azimuth; ϕ refers to tilt; and θ refers to high side angle.

CLAIMS

1. Well mapping apparatus, comprising

a) a magnetic field sensing device whose output is proportional to a local magnetic field vector,

b) an acceleration sensing device whose output is proportional to a local gravity vector, and

c) means supporting said devices for rotation about a common axis, in a borehole,

d) said outputs being usable in the determination of azimuth and inclination of the borehole.

2. Apparatus as claimed in claim 1, including means for simultaneously rotating said devices about said common axis.

3. Apparatus as claimed in claim 1 or claim 2, including circuitry operatively connected to receive the outputs of said devices to determine azimuth and inclination of the borehole.

4. Apparatus as claimed in any preceding claim, wherein said field sensing device comprises a magnetometer.

5. Apparatus as claimed in any preceding claim, wherein said means for rotating comprises a drive to continuously rotate the said devices.

6. Apparatus as claimed in any of claims 1 to 4, wherein said means for rotating comprises a drive to intermittently rotate said devices.

7. Apparatus as claimed in any of claims 1 to 3, including apparatus connected to receive the output of said field sensing means for providing an harmonic analysis of said output whereby errors in said azimuth determination, anomalies in the local magnetic field, or nearby magnetic objects may be detected.

8. Apparatus as claimed in claim 1, wherein the angularity of at least one of said devices relative to said common axis is canted.

9. Apparatus as claimed in claim 8, wherein said canted angularity is fixed.

10. Apparatus as claimed in claim 8, including means for adjusting said canted angularity periodically.

11. Apparatus as claimed in any of claims 8 to 10, wherein said one device is the magnetic field sensing device.

12. Apparatus as claimed in any of claims 8 to 10, wherein said one device is the acceleration sensing device.

13. Apparatus as claimed in claim 1, wherein the angularity of each of said devices is canted relative to said common axis.

14. Apparatus as claimed in claim 1, including a second magnetic field sensing device supported for rotation with said devices, providing an output usable in relation to the output of said magnetic field sensing device.

15. Apparatus as claimed in claim 14, including circuitry connected to receive the outputs of said magnetic field sensing devices and to average said outputs or azimuths determined therefrom.

16. Apparatus as claimed in claim 14, wherein the magnetic field sensing devices are spaced apart, and including circuitry connected to receive the outputs of said magnetic field sensing devices to derive a magnetic field gradient determination, said magnetic field gradients being usable to determine azimuth errors, anomalies in the local magnetic field, or nearby magnetic objects.

17. Apparatus as claimed in claim 1, wherein said devices and means are located in a borehole in the earth.

18. Apparatus as claimed in claim 17, including a cable suspending said devices and means in the borehole.

19. Apparatus as claimed in any preceding claim, including circuitry connected to receive the outputs of said first magnetic field sensing device and acceleration sensing device, and to process same to provide signals indicative of magnetic azimuth and tilt of the apparatus.

20. Apparatus as claimed in claim 14, including a device for sensing inertial angular rate supported for rotation with said first magnetic field sensing device and the acceleration sensing device and providing an output usable in relation to the output of said magnetic field sensing devices.

21. Apparatus as claimed in claim 14, and including circuitry connected to receive the outputs of said devices, and to process same to provide signals indicative of true azimuth, magnetic azimuth, tilt, and local magnetic anomalies or nearby magnetic objects.

22. Apparatus as claimed in claim 21, defining a magnetic variation survey tool.

23. Apparatus as claimed in claim 21, defining a combined single tool for magnetic azimuth determination, true azimuth determination, tilt determination, and detection of magnetic anomalies or nearby magnetic objects in a borehole.

24. Well mapping apparatus substantially as hereinbefore described with reference to, and as shown in, the accompanying drawings.

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